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ABSTRACT

Internal boundaries in multiphase flow greatly complicate fluid-dynamic and heat-transfer descriptions. Different flow regimes or topological configurations can have radically dissimilar interfacial and wall mass, momentum, and energy exchanges. To model the flow dynamics properly requires estimates of these rates. In this paper we define the common flow regimes for gas-liquid systems and describe the techniques used to estimate the extent of a particular regime. Also, we delineate the current computer-code procedures and introduce a potentially better method.

NOMENCLATURE

A = flow area, m^2
C = collision velocity, m/s
D = diameter, m
f = collision frequency, $1/t$
g = gravitational force, m/s^2
h = equilibrium height of liquid in a stratified flow, m
N = number density, $1/m^3$
S = source term, $1/m^3t$
t = time, s
U = critical velocity, m/s
V = velocity, m/s
 α = vapor volume fraction
 ρ = density, kg/m^3

Subscripts

b = bubble
g = gas
l = liquid
n = entity

1. INTRODUCTION

The existence of one or more fluctuating internal boundaries between phases or components is the important aspect that differentiates multiphase from single-phase flow. If accurate predictions of flow evolution are required, we must estimate the flow topology. In this paper, we generally consider gas-liquid internal flows but many of our comments also could apply to solid particles in a flowing fluid or to immiscible liquid-liquid systems.

In principle, if we can write the local instantaneous field equations for mass, momentum, and energy within each phase and if we know the suitable closure equations (or constitutive laws) both for the field-equation terms and for conditions across the interface, we can calculate the topology evolution. However, we must assume that accurate initial and boundary conditions are available. Because a liquid

film in the shearing process may produce 10^{10} droplets of varying sizes per cubic meter, we can make accurate predictions only for the most elementary cases.

Therefore, in most problems of interest we use simplified area or time-averaged field equations (1) or a lumped set of balance laws. Thus, a flow-topology specification that cannot be based completely on the most fundamental relationships must replace the information that is lost in the averaging process. The interfacial surface area will be orders of magnitude larger for liquid contained in droplet form than for the same quantity of liquid deposited entirely in a thin film on a pipe wall. This increase in surface area can affect greatly the interfacial heat mass and momentum transfer and, hence, the overall flow dynamics.

11. FLOW REGIMES IN GAS-LIQUID FLOWS

We have ascribed various adjectives to the flow patterns observed during experiments to provide some qualitative information. When the shape of the interface is determined experimentally, a fundamental difficulty exists. Experimentalists determine most flow regimes visually but have determined the topology by conductance probes (2), x rays (3), and pressure drops (4). Some experimentalists have assigned imaginative names to their observations but for our purposes we categorize the flow by the following basic set.

A. Bubbly Flow

Surface tension tends to produce spherical entities. At low vapor concentrations spherical bubbles form. The interfacial surface area per unit volume of vapor is large. As the flow develops, the bubbles may coalesce into larger bubbles; at moderate vapor fractions, large nonspherical vapor bubbles (slugs) develop.

B. Slug Flow

Slugs result from bubble coalescence. At vapor fractions greater than 0.3 for low- and moderate-speed flows, the bubble packing density becomes so great that coalescence virtually is ensured and large slugs form. However, in most cases, small bubbles that trail behind the slugs affect interfacial reactions.

C. Churn Flow

As the volume fraction increases, there may be insufficient liquid to support the liquid plug that separates the vapor slugs. The resultant, often oscillatory, flow has convoluted strings of vapor and liquid intermixed and generally is named churn-turbulent flow.

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D. Annular-Mist Flow

At higher vapor fractions, a liquid annulus may form on the conduit wall. If the vapor velocities become high enough, droplets may form in the center of the flow.

E. Separated Flow

If the flow occurs in a horizontal plane at low vapor velocities and moderate vapor fractions, separated or wavy-separated flow may occur; that is, the flow may separate into a vapor layer at the top of the pipe and a smooth or wavy, fluctuating liquid film at the bottom. Also, axisymmetric flows normally are not maintained in horizontal pipes for any flow patterns except at very high flow rates.

III. TECHNIQUES USED TO SPECIFY THE FLOW REGIME

The first technique used to specify flow regimes, and the one that is most widely used today, is the flow-regime map; that is, the map shows regions that represent transitions between flow topologies and that generally are functions of at least the liquid and vapor flow rates. Maps may be based on dimensionless or, more commonly, dimensional quantities. Scott (5) has modified one of Baker's earliest maps (6) for horizontal adiabatic flow. Mandhane et al. (7) have a formulation that uses simpler variables. However, these techniques, which apply to fully developed (if any two-phase flow can be considered fully developed) steady-state flows, cannot account for rapid transient effects, entrance effects, or the manner in which a discontinuous phase is introduced into a continuous phase. At best, these maps are guides to flow transitions; they are based on insufficient physical characteristics and, thus, cannot be used to extrapolate beyond the data range available to generate the plots.

During the last decade, analysts have tried to develop mechanistic models to predict flow transitions. This approach has the principal advantage that it can be applied to many fluids and flow conditions although it still may not compute rapid transient and entrance effects accurately.

Radovich and Moirais (8) proposed a problem in which the bubbles had a diameter of D_b , existed in a cubic lattice, and had a velocity c , relative to each other. They calculated a collision frequency f that is proportional to F ,

$$F = \frac{C}{D_b \left\{ \frac{(0.741)^{1/3}}{\alpha} - 1 \right\}^5} \quad (1)$$

This void fraction dependence suggests that the transition from bubbly to slug flow becomes highly probable at an alpha greater than 0.3, which has been experimentally observed. Their model is simple and does not account for active surface agents or hydrodynamic forces between the bubbles that can influence the coalescence of bubbles into slugs. In particular, bubbles in froths or foams can exist at much higher void fractions than Eq. (1) suggests is possible. High mass flow rates also may prevent bubble coalescence. Nicklin and Davidson (9) have linked the transition between the slug and churn-turbulent regimes in vertical pipes to flooding phenomena. Flooding occurs when the vapor drag on the liquid is sufficient to prevent its injected film from settling to the bottom of the pipe. Although

the Wallis correlation (10) often is used to estimate the flooding point, it sometimes is inappropriate.

If the superficial vapor velocity increases above the flooding limit (for a fixed liquid flow), the liquid velocity reverses, which apparently is the transition point from churn-turbulent to annular flow.

Taitel and Dukler (11) identified five basic flow regimes for horizontal pipes: stratified, wavy stratified, intermittent, dispersed bubbly, and annular. The intermittent flow included any regime with elongated bubbles. If the bubbles almost filled the tube completely, they were called slugs; if the bubbles did not fill the tube, they were called plugs. Their basic procedure started with a stratified flow and examined the mechanisms that caused wave generation and liquid-plug formation. For the transition between stratified and intermittent flow, a critical Froude number based on the vapor velocity was the important quantity.

$$U_2 > (1 - \frac{h}{D}) \left[\frac{(\rho_L - \rho_G) g A_R}{\rho_G \frac{dA_L}{dn}} \right] \quad (2)$$

where h , A_R , and dA_L/dh are derived from meniscus relationships for an undisturbed stratified flow. This transition is the most important of the five for calculating many horizontal pipe problems. In nuclear-reactor-safety systems codes, this transition is the most important for horizontal-pipe calculations because the interfacial drag changes dramatically when large waves develop. When this transition occurs, the flow from the reactor vessel to the steam generator can change from countercurrent to cocurrent, causing a change in the cooling mechanism.

IV. COMPUTER-CODE PROCEDURES FOR CALCULATING FLOW REGIMES

Computer codes used to analyze two-phase flow problems can solve the basic mass, momentum, and energy field equations in complicated geometries. However, because the interfacial exchange terms in the more complicated models can vary widely as a function of flow regime, some flow-topology formula for the exchange terms is necessary.

Some of the first six-field-equation codes (separate mass, momentum and energy conservation laws for each phase) used extremely simple flow algorithms. In the KACHINA program (12), as the void fraction $\alpha \rightarrow 0$, a bubbly flow was used; but, as $\alpha \rightarrow 1$, droplet drag was used. The weighting factors, α and $(1 - \alpha)$, on the two terms implied that bubbles and droplets coexisted equally; that is, liquid and vapor were simultaneously continuous and discontinuous at a void fraction of 0.5. Even though the main virtue of this technique was its simplicity, the method produced reasonable results for high-speed flows where the phases normally were well mixed.

However, nuclear-reactor-safety systems codes must calculate a wide range of transients; therefore, they need to consider a wider range of flow regimes than just bubbles and droplets. The Transient Reactor Analysis Code, TRAC (13), incorporates a level of complexity for two-phase flow analysis that is representative of most state-of-the-art codes. The basic TRAC flow-regime map is a simple one that is based on a void-fraction dependency. If $\alpha < 0.3$,

a bubbly flow is used: whereas, in the range $0.3 < \alpha < 0.5$, the vapor coalesces linearly with the void fraction into slugs as long as the overall mass flux is below a critical value. The area, $0.5 < \alpha < 0.75$, is a churn region that has a drag, located intermediately between a bubbly-slug and an annular-mist shear. If $\alpha > 0.75$, either an annular or annular-mist flow with an entrainment is used to determine the percentage of liquid contained in the core in droplet form. If the flow occurs in a horizontal pipe, Taitel and Dukler's analysis (Eq. 2) is used to determine if a stratified flow exists. Although the model is extremely simple, reasonable results have been obtained for a wide variety of problems. Figure 1 illustrates these relationships.

However, a more interesting approach replaces the current flow-regime determination with differential equations for interfacial surface area or entity number density.

Number-density equations for the number of entities of the discontinuous phase/unit volume could be written in the form,

$$\frac{\partial N}{\partial t} + \nabla \cdot (NV_N) = S \quad (3)$$

The source term S covers many effects such as generation, coalescence, or disappearance of the entities; also, it might involve differential terms. The closure or constitutive equations would use the resulting number density N to calculate the interfacial interactions.

It is exceptionally easy to add one or more equations of the form of Eq. (3) to the semi-implicit numerical scheme (14) used in many existing codes. The basic calculational technique involves the solution of field equations by whatever method currently is in use and then performs an explicit pass on Eq. (3) using the updated velocities V produced during the time step as well as the updated variables in the source term S . Then, the following time step would use the resulting number densities to calculate the interfacial terms. The increase in cost is very modest for any large computer program that already can solve a complicated field-constitutive equation set.

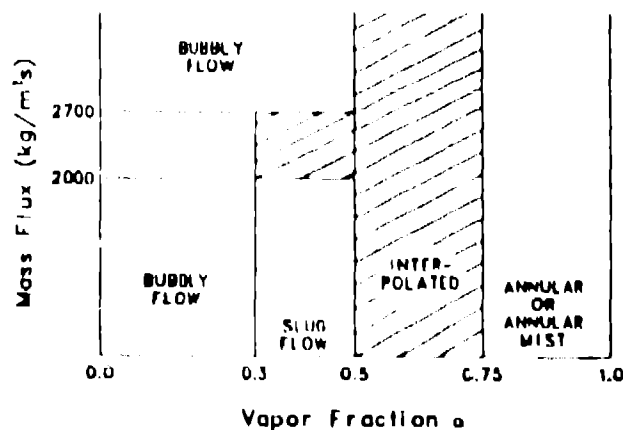


Fig. 1 TRAC flow-regime map

Consider the problem where subcooled liquid in a boiler tube is heated such that bubbles form and eventually coalesce into slugs. As vaporization continues, the void fraction and the vapor velocity increase and the slugs break down into a churn-turbulent regime and finally into an annular-mist regime. This would be reflected by dramatic changes in the number density for a one-dimensional representation of the tube would reflect these dramatic changes.

Before the point of net vapor generation, the terms N and S would be zero. At the point of net vapor generation, which could be determined by the Saha-Zuber criterion (15), S would become greater than zero and V_N would become V_g . However, at this point a real difficulty still exists. Although data on the number of active nucleation sites for heterogeneous nucleation as well as data on the frequency rate of bubble production at these sites are available, both surface finish and the purity of the working fluid can affect these terms greatly. It may be impossible to specify a source term for bubble generation without using one or more adjustable parameters. As the bulk of the fluid reaches the saturation temperature and the void fraction increases, the number density also will increase.

However, coalescence will occur as the vapor fraction grows and Eq. (1) could be used as a starting point to derive a negative source term for this effect.

A churn-turbulent region normally separates a continuous-liquid from a continuous-vapor domain. Thus, the entire concept of entities with specific geometric characteristics may become meaningless in this flow topology. We think that it may be plausible to write both vapor and liquid number-density equations for this regime with the understanding that these number densities may be useful only to detect the existence of this particular chaotic topology, not to calculate the interfacial relationships.

Finally, as the vapor number density approaches unity, the transition from churn-turbulent to annular flow is complete. If entrainment is present, there would be source terms in the liquid number-density equation to reflect the entrainment and deposition of droplets. Several codes (16) successfully have incorporated either number-density or interfacial surface-area transport equations for the droplet regime.

A model constructed with interfacial-area or number-density equations still would not be a first-principles calculation. However, it potentially would provide a much better estimate of the actual topology when entrance or temporal effects were present and, thus, could improve calculated results. The source terms for equations of this form still need to be defined but the potential rewards for this effort are great.

A study of flow regimes absolutely is essential to an understanding of two-phase flow. Without such information only very crude estimates of interfacial and wall exchanges can be made. Although some progress has been made in providing tools to use in estimating the proper topology, much effort still is required to improve the predictions.

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